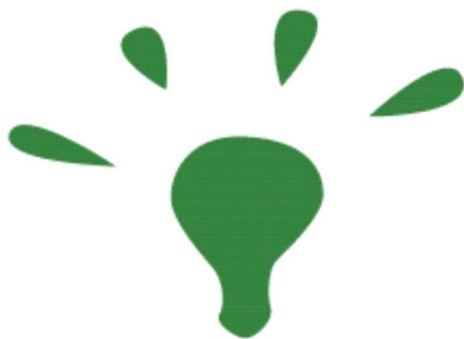


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Clean
Manufacturing

Sustainable Solutions



Clean Manufacturing, *Reimagined.*

CleanTech for Improved
Yields, Productivity, and
Profitability

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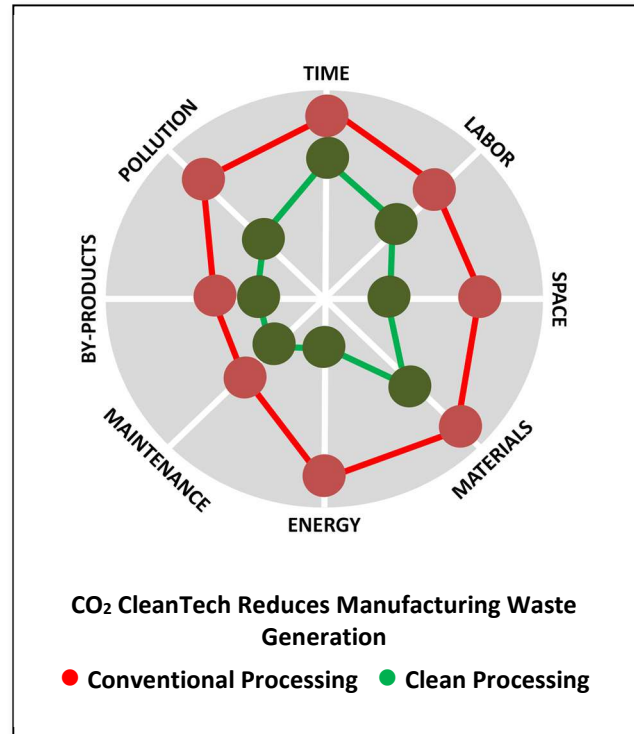
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Introduction to Clean Manufacturing

For more than 25 years, our CO₂-based clean manufacturing technology (CO₂ CleanTech) has been used by companies in the aerospace, medical, hard disk drive, and microelectronics industries for precision cleaning and cooling-lubrication applications. CO₂ CleanTech has been used in high technology, high reliability, and high capacity manufacturing operations to improve the cleanliness of components, assemblies, tools and fixtures. More significantly, CO₂ CleanTech has proven to be a cost- and performance-effective means for reducing multifaceted forms of manufacturing waste - processing time, production space, labor and energy inputs, maintenance activities, by-product production (scrap and waste input material), and environmental pollution (air, water, and solid waste).



In an environment of intensifying manufacturing challenges such as global competitiveness, environmental regulation and energy supply issues, managers must have both lean and green (clean) manufacturing technology to eliminate multifaceted manufacturing wastes in their operations that stealthily steal away business profits. CO₂ CleanTech represents a significant business opportunity for those manufacturers that can adapt their production tools to meet the new challenges ahead. Moreover, the merging of green practices into lean manufacturing promises to deliver additional value in the form of less chemical, energy, labor, and water usage.

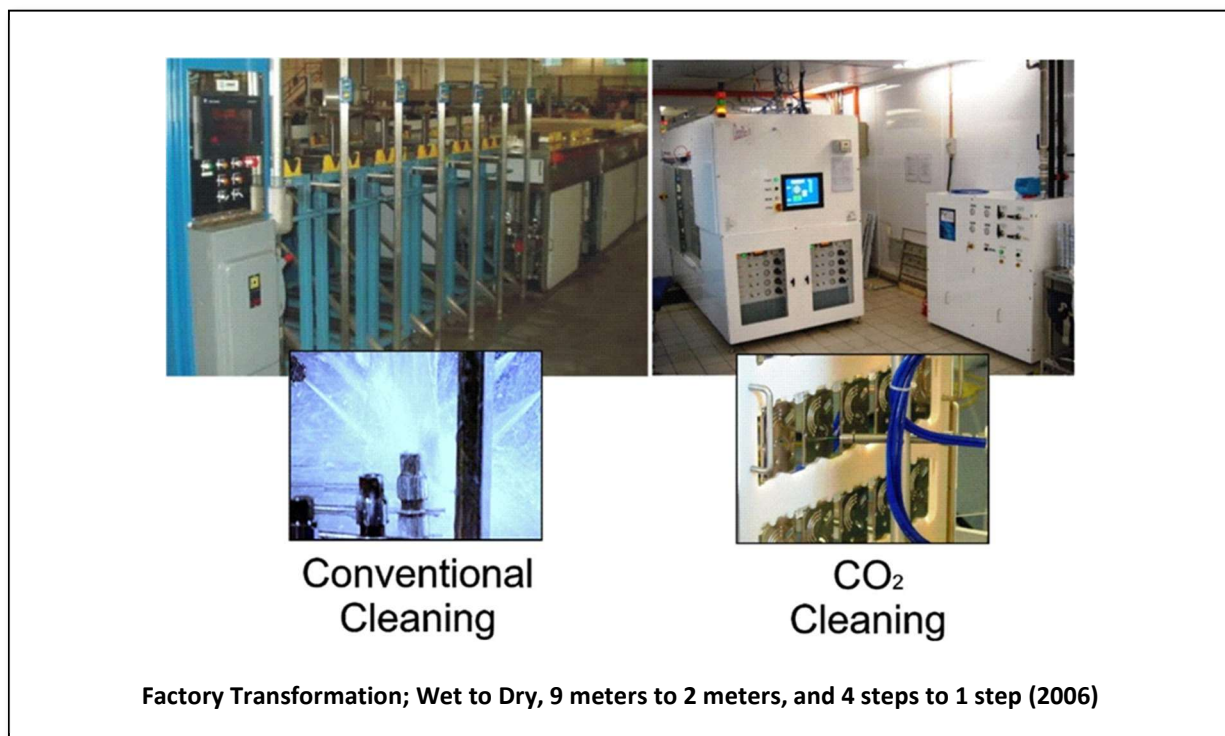
CO₂ CleanTech provides manufacturers, component suppliers and equipment suppliers with new ways to re-tool their production lines for clean production. For example, manufacturing tool builders can develop and deliver clean-in-place assembly process-tool combinations to support sustainable manufacturing initiatives. Component suppliers can produce and supply better quality product at lower cost. device manufacturers can adapt dry clean-in-place capability



throughout the factory. CO₂ CleanTech significantly reduces or even eliminates many forms of lean and green manufacturing waste throughout the production line, and in numerous and unique ways.

Need for Cleaner Production

Manufacturing waste is generally thought of as any resource used in a production process that does not go out as part of the product and/or costs money to get rid of it. However, manufacturing waste also exists in many other forms, for example excessive factory space utilization for equipment (production and waste treatment equipment), inefficient material and



process flows, inefficient use of facility labor and lost productivity of both labor and equipment. These types of wastes significantly impact a company's bottom line too, but are often obscured in overhead accounts or generally overlooked in the manufacturing operation.

In an era of complex business challenges; intense global competitiveness, increasing environmental regulation and energy supply issues, managers must have both lean and green (clean) manufacturing skills necessary to identify and eliminate multifaceted manufacturing wastes in their operations that stealthily steal away business profits. Leading companies in the high tech manufacturing industries are moving beyond just producing high capacity, low-power products. For example Seagate Technologies, a hard disk drive manufacturer, is implementing various environmentally protective manufacturing initiatives, summarized on their website. The supply chain in this industry is also implementing cleaner production techniques to reduce energy

inputs and product defects (Chompu-inwai et al, “Application of Cleaner Technology Concepts in the Arm Coil Assembly Process of Hard Disk Drive Manufacturing”, Proceedings of the International Conference of Engineers and Computer Scientists, 2010, Volume III).

High tech, high reliability manufacturers require state-of-the-art clean manufacturing technology and implementation strategies for successful design and execution of manufacturing waste reduction programs. Manufacturing waste reduction programs involving CO₂ CleanTech provide a combination of possibilities (and benefits), including:

- CO₂ CleanTech eliminates or reduces composite forms of manufacturing waste: time, labor, space, transport, defect, inventory, processing, equipment, raw materials, air pollution, water pollution, wastewater, solid wastes, and energy wastes.
- CO₂ CleanTech improves quality and reliability requirements imposed by advanced materials, manufacturing methods and processes, and new performance standards.
- CO₂ CleanTech integrated into flexible automation, modular and clustered assembly operations (cells) eliminate repetitive operational task errors and reduce skilled labor wastes.
- CO₂ CleanTech integrated into tools and processes produces more adaptable and flexible production tools and methodologies which improve efficiency and productivity in high volume or high tech production operations.

CO₂ is a Unique Manufacturing Waste Reduction Solution

CO₂ is a safe and abundant compound that plays a very important role in many commercial and industrial applications. Leading companies have implemented CO₂-based cleaning technology and have realized improved productivity and a lower cost-of-operation of their production operations. CO₂ CleanTech has also served as a strategy for complying with worker safety and environmental regulations. The CO₂ used in cleaning, machining and thermal control products and processes is the same CO₂ used to charge fire extinguishers, carbonate beverages, weld steel, cast metals, and refrigerate products, among many other important industrial uses. In fact it’s the same CO₂ that you are exhaling while reading this brief; about 1 Kilogram of it every day. It is an abundant by-product of



**Recycled Carbon Dioxide is
Used for Cleaning, Cooling
And Machining**

numerous industrial and natural processes that is recycled into other useful operations rather than wastefully discharged into the atmosphere. Recycled CO₂ is a valuable and renewable manufacturing resource that will never run out of supply. Unique benefits derived from using recycled CO₂ include the conservation of water, reduced energy consumption and a reduction in

industrial CO₂ emissions. Moreover, CO₂-based process technology is a positive contribution to Hazardous Air Pollutant (HAP), Volatile Organic Compound (VOC), and Greenhouse Gas (GHG) emissions reduction strategies.

Using recycled CO₂ to reduce pollution, conserve energy and eliminate wastes (both environmental and manufacturing) produces numerous tangible and measurable benefits.

Consider the following. Major industrial sources of CO₂ emissions include:

1. Electrical power generation and usage,
2. Chemical generation and usage, and
3. Transportation.

The use of recycled CO₂ technology as a chemical/process substitute lowers electrical power usage, reduces manufacturing wastes, increases manufacturing productivity, and decreases the need for chemicals such as lubricants and solvents, among many other positive socioeconomic and environmental benefits. A reduction of manufacturing wastes or elimination of production chemical inputs of any kind decreases industrial CO₂ generation. Following are examples of how this works:

- ✓ Less CO₂ is produced if less electricity is consumed for processing.
- ✓ Less CO₂ is produced if less oil is refined, transported and consumed.
- ✓ Less CO₂ is produced if less cleaning solvents are produced, transported and consumed.
- ✓ Less CO₂ is produced if more products can be manufactured for the same energy, labor and space inputs.
- ✓ Less CO₂ is produced if products don't have to be cleaned using hot deionized water or dried using solvents or other drying agents.

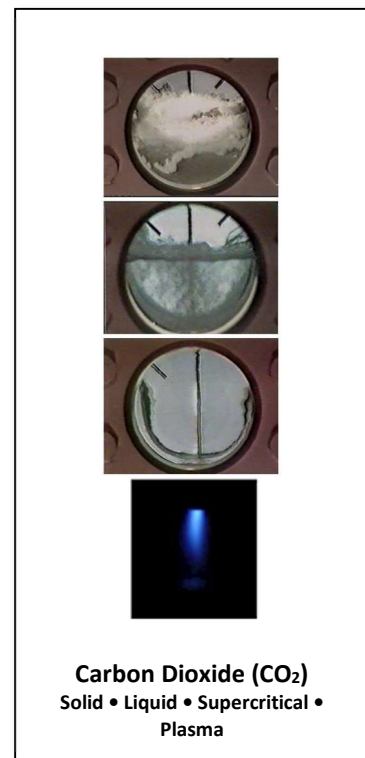
Thus from a GHG emissions perspective, using recycled CO₂ significantly offsets new CO₂ gas production and emission from both the industrial supply and consumption sides of the equation. USEPA legislation coming down the pipeline with regards to CO₂ emissions reporting is intended to impact the "generators" of CO₂. A user of recycled CO₂ is not considered a generator of CO₂. The CO₂ used in commercial and industrial processes is already accounted for in the GHG emissions inventory.

With regards to smog generation, CO₂ is not a VOC and is not regulated as such. From a worker health and safety perspective, CO₂ is non-toxic. From a building safety and equipment protection perspective, CO₂ is non-flammable and non-corrosive. CO₂ is a perfect solution for protecting the environment and improving the health and safety of both workers and communities, while improving the performance and cost-of-operation of supplier and manufacturing operations.

CO₂ is Many Manufacturing Agents in One

CO₂ is a very remarkable manufacturing agent. It can be used as a spray, immersion solvent, extraction solvent, and plasma in the form of composite sprays, hybrid solid-plasma sprays, centrifugal liquid carbon dioxide cleaning systems, and supercritical fluid extraction systems. In addition, CO₂ fluids purification and management systems have been developed to support these various capabilities. CO₂-based manufacturing and industrial applications are as diverse. Applications for CO₂ CleanTech include precision degreasing, decontamination, outgassing, drying, disinfection, surface modification and functionalization, cooling and lubrication, among many others.

CO₂ physical and chemical properties are similar to HFE and CFC solvents such as Freon[®] 113 and HFE-7100. CO₂ possesses a Hildebrand solubility parameter in the adjustable range between 14 MPa^{1/2} to 22 MPa^{1/2} depending upon phase, temperature and pressure. CO₂ can be compressed to a range of liquid-like densities, yet it will retain the diffusivity of a gas with extremely low viscosity. Supercritical and liquid CO₂ cleaning agent densities may be adjusted between 0.5 g/cm³ and 0.9 g/cm³. Solid phase CO₂ has a density of 1.6 g/cm³, identical to Freon 113. Surface tensions range from 0 dynes/cm (supercritical) to 5 dynes/cm (liquid). Practical benefits derived from these unique properties include rapid penetration and wetting, oil solubility and, cooling and dry lubrication effects.



CO₂ CleanTech Reduces or Eliminates Manufacturing Waste

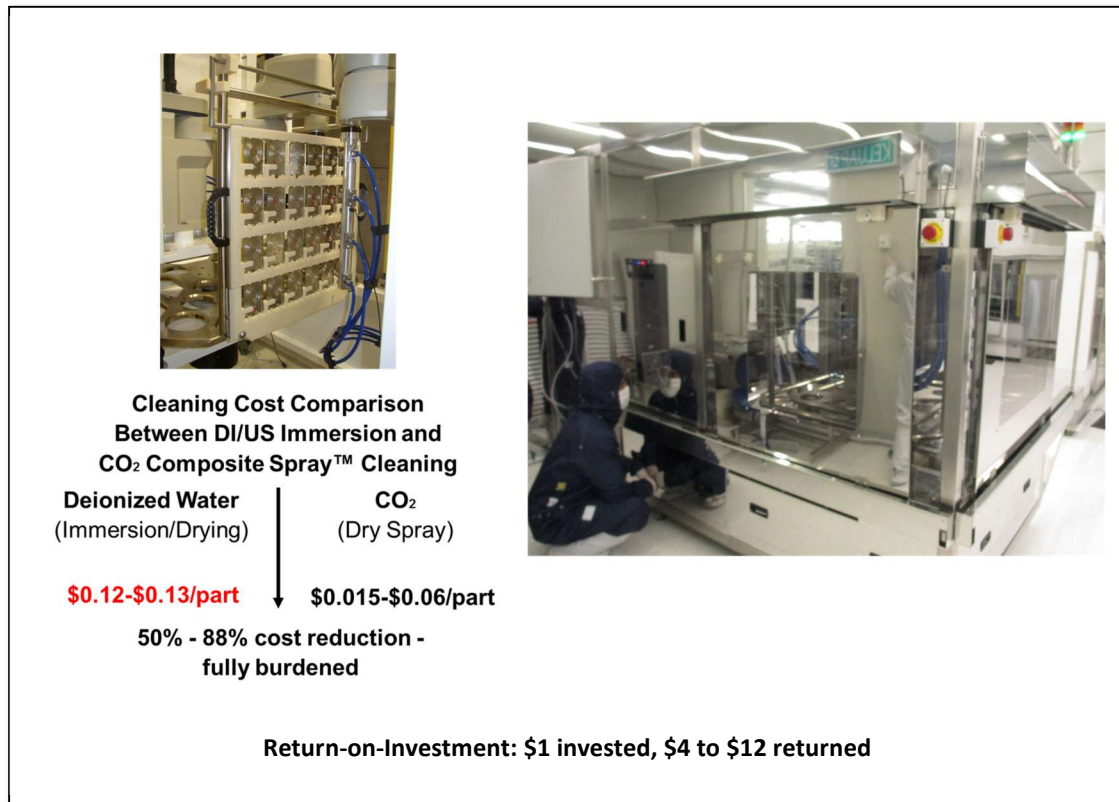
CO₂ CleanTech eliminates or significantly reduces waste generation at the production operation level (i.e., at the source) by modifying manufacturing processes, and in particular precision cleaning, assembly processes requiring critical cleaning, and precision machining operations. CO₂ modifies conventional manufacturing processes and tools in several dimensions, described as follows;

1. Physically; shape, size, space, application and configuration;
2. Chemically; solvency, toxicity, and dryness;
3. Quality; defects, rework, scrap; and
4. Time; productivity.

CO₂ CleanTech may be implemented in a variety of production equipment and process configurations to meet the needs of lean production schemes and product flow constraints, including both existing and new production tool and line implementations.

Examples of manufacturing activities that produce manufacturing waste include:

- Moving products off-line or out of cells to clean them and then returning them back to the line or cell
- Filtering and treating spent alkaline cleaning chemistries
- Monitoring cleaning and machining fluid chemistries
- Rinsing parts with deionized water
- Drying parts with compressed air or alcohol
- Treatment and disposal of spent dicing, cleaning and machining agents
- Completing waste hauling manifests
- Preparing environmental reports
- Deionized water treatment
- Rinse water treatment and disposal
- Disposal of spent filters and sludge



Given this capability, consider how CO₂-enabled production operations can eliminate many different forms of manufacturing waste:

- **Space and process step reduction:** CO₂-enabled cleaning processes can reduce multiple processing steps to a single step and perform in less space, sometimes no extra space is needed if the CO₂ process is integrated directly into/onto a new or existing manufacturing tool such as a bonder, dispenser, or machining tool.
- **Materials selection and productivity:** Recycled CO₂ itself does not generate waste, does not require environmental management, and eliminates equipment cleaning and maintenance.
- **Energy conservation:** Using recycled CO₂ eliminates the need for additional energy to heat cleaning baths, dry parts, or evaporate and concentrate wastes.
- **Waste reduction and elimination:** CO₂ does not itself become a waste by-product. CO₂ eliminates the wasteful consumption, treatment and disposal of water, wastewater and associated solid wastes.
- **Air pollution reduction:** CO₂ is not considered an air pollutant, is non-toxic and is odorless within the factory atmosphere.

Examples of unique CO₂-enabled production configurations and manufacturing waste reduction benefits are summarized in Table 1.

Table 1
Examples of
CO₂ CleanTech Benefits

Equipment and Process Configuration	Waste Reduction Benefits
Integrate CO ₂ CleanTech with automation and environmental control to produce custom stand-alone automated cleaning cells or islands to replace aqueous and solvent cleaners.	Eliminate aqueous cleaning and rinsing fluids, drying equipment and related waste-producing operations.
Integrate CO ₂ CleanTech into existing production lines and processes.	Enables in-line cleaning where none existed and without an increase in floor space.
Hybridize CO ₂ CleanTech with one or more assembly processes such as dispensing, bonding, welding, coating, curing, soldering, and inspection to form clean-assembly cells.	Eliminate the need for separate and additional cleaning equipment, processes and related waste-producing operations.
Integrate CO ₂ CleanTech with machining and metalworking tools to enable minimum quantity cooling lubrication.	Improve surface finish – less defects. Eliminate flooded lubrication and follow-on cleaning operations.

CO₂ CleanTech Implementation in the Production Network

CO₂ CleanTech can be implemented throughout the production network. Following are some examples and benefits:

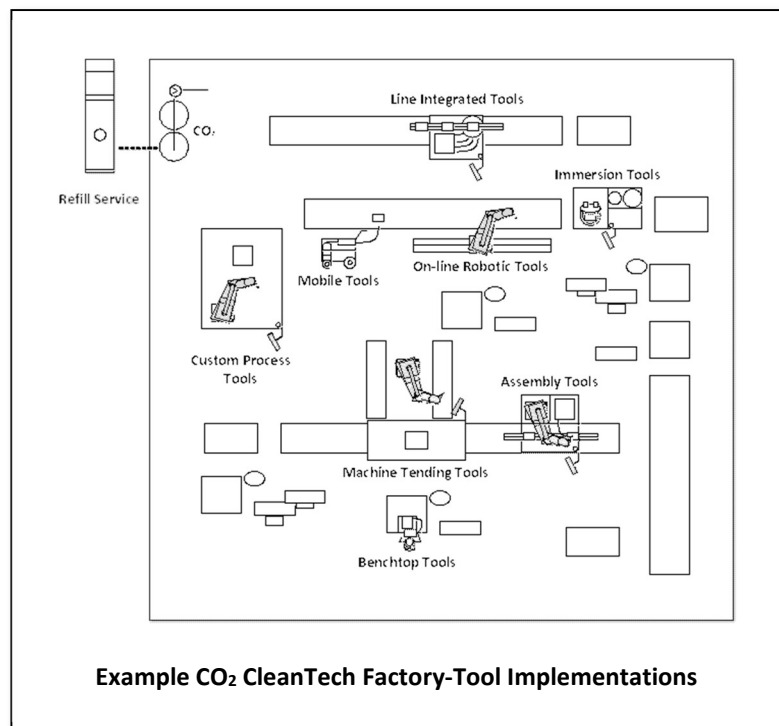
- **Tool Builders** – Production of new, hybrid clean-, cool-, or lubricate-in-place manufacturing tools (Clean-Assembly Tools).
- **Component Manufacturers** – More profitable operations and cleaner products produced.
- **Automation and Robot Suppliers** – Integrate robots with CO₂ Processor Unit (CPU™) and assembly technology to provide drop-in-place reconfigurable automated clean assembly solutions.
- **Production Line Builders** – Integrate CO₂ technology into new factories to decrease space, improve product flow and process efficiency.
- **Contract Cleaning Service Providers** – Utilize CO₂ cleaning rather than aqueous or solvent technology for more profitable operations and cleaner products.
- **Device Manufacturers** – Adapt existing production lines, tools, and processes with CO₂ technology to enable cellularity, lean operation and green production.

CO₂ CleanTech can be integrated into virtually any machine, equipment platform, and process to provide in-situ dry, clean surface treatment, process thermal control and cooling-lubrication. CO₂ CleanTech performs these functions without producing air pollution, wastewater or solid wastes, and enhances product yield, tool productivity and increases energy savings.

Following are examples of implementation:

- Mobile tools, including mobile robotic tools
- Production line integrated tools
- Manufacturing tools (Clean-Assembly tools)
- Cellular or island cleaning tools
- Robot-enabled tools, including tenders
- Work bench tools

CO₂-enabled cellularity is very productive because two or more value-add manufacturing operations can be performed



along with non-value-add cleaning, cooling, and lubrication within the same work space. Products don't have to be removed, transported, cleaned and returned - resulting in reduced movement, smaller footprints, less human interaction, higher throughput, and decreased cost-of-assembly. Products stay cleaner with less movement as well.

CO₂ CleanTech Transforms Manufacturing (Conclusion)

It has been 250 years since carbon dioxide (CO₂) was discovered by Joseph Black, about 150 years since the first discovery of CO₂'s remarkable chemical properties, and 35 years since the first CO₂ precision cleaning applications were developed at Hughes Aircraft. Today, CO₂ CleanTech is being used commercially in many ways throughout industry to address a variety of manufacturing challenges. CO₂ CleanTech serves as an alternative to many conventional surface immersion, extraction, spray and plasma cleaning and treatment processes. The work performed over the past three decades has demonstrated that CO₂ CleanTech is uniquely versatile and adaptable to the production of a diverse array of manufactured products ranging from radial tire molds to guidance gyros, automobile fuel injectors to spacecraft materials, and aircraft engines to disk drive components. More recently, CO₂ CleanTech has found its way into machining operations as a replacement for flooded coolants, and more specifically to address the higher cutting heat demands of advanced materials such as ceramics, superalloys, and titanium. CO₂ CleanTech provides a better, faster, cleaner and lower cost solution for many manufacturing applications.

Aspect	Examples
Processes	Plant Extraction, Fastening, Welding, Machining, Stamping, Thermal Spray, Coating, Molding, Testing, Inspection, Wire Bonding, and Adhesive Bonding...
Wastes	Motion, Space, Energy, Inventory, Transport, Tool Life/Changes, Safety, Scrap, Environmental Permitting, Pollution, Water, Labor, Capital, and Rework...
Functions	Value Extraction, Degreasing, Thermal Control, Disinfection, Defluxing, Bioburden Reduction, Outgas Removal, Surface Modification, and Dry/Near-Dry Cooling-Lubrication, Precision Drying, and Pressure Impregnation...
Implementations	Integrated with a Pressure Vessel, Process Tool, Conveyor, Stand-alone Tool, Cluster Tool, Mobile Tool, and Robotic Tool...
Quality	Higher Yields, Cleaner Environment, Safer Environment, Better Surface Finish, Higher CpK, Improved Product Performance, and Improved Dimensional Control...

CO₂ CleanTech Transforms Manufacturing

CO₂ CleanTech has been used in ways not possible using conventional technologies such as aqueous and solvent cleaning technology and more recently machining coolant technology. This is characteristic of a transformational manufacturing technology. A transformational technology changes the “value networks” for the manufacturing industry. Value networks comprise sales and distribution channels, performance standards, suppliers and product and services forms, among other elements. New value networks – the creation of new contexts of consumption and competition – are currently being developed for CO₂ CleanTech to realize its full potential throughout the manufacturing industry.

As illustrated in this white paper, CO₂ CleanTech delivers real, measurable value in the form of adaptability, configurability, increased productivity, and improved product quality. Tangible financial benefits include manufacturing cost reductions derived from energy conservation, decreased material and labor inputs, among many other manufacturing waste reductions.

About Us

Clean Imagineering LLC (Clean Imagineering) and CleanLogix LLC (CleanLogix) are related but independent business operations. Clean Imagineering heads up clean manufacturing business development and serves as the sales-distribution group partner. Cleanlogix, a division of Clean Imagineering LLC, provides exclusive engineering-manufacturing support services to Clean Imagineering.



Clean Imagineering and CleanLogix are co-headquartered in Santa Clarita, California. The companies collaborate closely to develop innovative and practical clean manufacturing solutions for end-users, OEMs, integrators and line builders, which is based on a strong foundation comprising more than 35 years of CO₂ technology development and commercialization experience. Core competency encompasses the use of recycled carbon dioxide as a green chemistry for value extraction, precision cleaning, minimum quantity cooling-lubrication, and thermal control applications. Both large and small manufacturing companies have realized significant manufacturing waste reductions employing the companies CO₂ CleanTech innovations.

Additional Reading

Demonstration of a Liquid Carbon Dioxide Process for Cleaning Metal Parts

United States Environmental Protection Agency (USEPA)
Field Demonstration – Warner Robin Air Force Base
Technical Evaluation Report EPA-600/R-96-131
November 1996

Using CO₂ Snow to Correct Drive Level Dependence in Quartz Crystal Resonators

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Precision Cleaning and Machining with Minimal Waste and Increased Productivity

D. Jackson
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Effective Alternatives to Traditional Spray and Immersion Cleaning Processes

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Process Cleaning Magazine
March/April 2007

Machining with Advanced Minimum Quantity Cooling-Lubrication (MQCL) Technology

Neil Canter, PhD, Editor
Tribology and Lubrication
July 2007

Preliminary Evaluations of Composite CO₂ Spray as a Machining Lubricant in Hard Turning and Conventional Milling

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ASME/STLE International Joint Tribology Conference Proceedings
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October 2007

CO₂ for Thermal Spray Advances

D. Jackson et al.
Spraytime
The International Thermal Spray Association
Volume 16, Number 1
First Quarter 2009

Automated CO₂ Composite Spray Cleaning System for HDD Rework Parts

G.W. Knoth Western Digital Corporation, D.P. Jackson and NW. Sorbo, Cool Clean Technologies, Inc.
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Setting the Record Straight: CO₂ Technology is Part of the Solution
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July/August 2012

Cleaning Injection Molded Silicones and other Polymers with CO₂

D. Jackson
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Particulate Removal using a CO₂ Composite Spray Cleaning System

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Carbon Dioxide Spray Cleaning for Modern Manufacturing

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Ceramics International Magazine
Volume 166 Issue 11
November 2016



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CLEANLOGIX
a division of Clean Imagineering LLC

767 Hawthorne Avenue Unit B
Ponderay, Idaho 83852 U.S.A.
<https://www.cleanimagineering.com>
+1 (661) 430-6767